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PRIORITIZING LEAN CONSTRUCTION PRACTICES FOR EFFECTIVE MEGAPROJECT DELIVERY

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ABSTRACT

Megaprojects, characterized by their complexity, large scopes, and diverse stakeholders, often face inefficiencies, cost overruns, and uncertainties. Lean Construction (LC) has emerged as a transformative approach to address these challenges, enhancing efficiency, collaboration, and sustainability in megaproject delivery. This study bridges the gap between theory and practice by developing a comprehensive LC implementation model for megaprojects. It focuses on three objectives: identifying key LC practices through a literature review, validating them via expert interviews, and ranking them using the Fuzzy Relative Importance Index (FRII)

Employing a mixed-methods approach, the research combines a systematic literature review, expert insights, and a survey of 379 construction professionals to evaluate and rank critical LC practices. The study identifies 35 essential practices, with Integrated Project Delivery (IPD) systems as the most critical, followed by the Last Planner System (LPS), Value Stream Mapping (VSM), Building Information Modelling (BIM), and Target Value Design (TVD). These practices address barriers to LC adoption and megaproject challenges. By providing a prioritized framework, the study offers actionable insights for industry leaders and policymakers, enabling them to focus on impactful strategies for sustainable megaproject delivery. The findings advance LC theory and provide practical tools for driving innovation in the construction industry.

KEYWORDS

Lean Construction; Megaprojects; Complex; Fuzzy Relative Importance Index; Sustainability.

INTRODUCTION

Mega infrastructure projects, or large-scale projects, are complex ventures that significantly contribute to the political, economic, social, scientific, and technological advancement of a country or region. These projects aim to provide essential public services or drive socio-economic development, playing a crucial role in achieving sustainable growth (Shi et al., 2024). However, their complexity marked by numerous stakeholders, substantial capital investments, and extensive human resources introduces high risks, often exacerbated by the interconnected nature of subsystems (Chen et al., 2024). Consequently, uncertainties and misaligned stakeholder objectives frequently arise, complicating project execution. Successful megaproject planning and execution demand extensive collaboration among stakeholders, leveraging diverse expertise and resources to foster innovation and achieve project goals (Locatelli et al.,

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2021). Yet, despite these efforts, megaprojects often underperform, suffering from cost overruns, delays, and suboptimal outcomes. Flyvbjerg (2017) reports that nine out of ten megaprojects exceed their budgets. In China, for instance, railroad projects experience an average cost overrun of 30.6%, with delays extending to 25% (Flyvbjerg, 2016). To mitigate these challenges, new methods and theories are urgently needed to address the unique complexities of megaprojects in both practical and theoretical contexts. LC has emerged as a promising solution in megaprojects (Ibrahim et al., 2025).

LC is a continuous improvement process that reduces waste, enhances productivity, and improves health and safety while meeting client expectations and promoting sustainability. In construction megaprojects, LC has demonstrated potential in addressing inefficiencies, cost overruns, delays, and stakeholder misalignment. Studies highlight its effectiveness in improving collaboration, communication, and overall project performance. For example, the Mohamed VI Tower project utilized LC tools to significantly reduce quality defects and enhance customer satisfaction (Idrissi Gartoumi et al., 2023). Similarly, integrating Building Information Modelling (BIM) with lean methodologies in the Istanbul Grand Airport (IGA) project accelerated design iterations, improved documentation coordination, and minimized redundancies, leading to higher-quality outcomes. Further reinforcing LC’s benefits, the Cathedral Hill Hospital (CHH) project in San Francisco demonstrated how LC enhances collaboration, reduces waste, and eliminates rework in complex design processes (Lostuvali et al., 2014). Despite the demonstrated benefits of LC in megaprojects, significant research gaps remain in its adoption and implementation. Key gaps include the lack of clear identification and prioritization of critical LC practices, which limit the ability to strategize its effective implementation. Additionally, published models of LC practices vary widely in their focus—some emphasize waste reduction, others stakeholder collaboration, and others integration with digital tools like BIM. These inconsistencies underscore the need for a systematic and unified approach to identifying and assessing the criticality of LC practices most effective for megaproject delivery. This study aims to address these gaps by providing a clearer framework for implementing LC, bridging the divide between theory and practice:

1. What are the key LC practices that are most effective for managing megaprojects?
2. How can these practices be systematically prioritized to facilitate their adoption in megaprojects?

By addressing these questions, this study contributes to both theory and practice by providing a structured framework for implementing LC in megaprojects. Therefore, the objectives of this study are:

1. to identify key LC practices through an extensive literature review.
2. to validate these practices via expert interviews.
3. to prioritize them to facilitate widespread adoption.

RESEARCH BACKGROUND

EVALUATION OF EXISTING LEAN CONSTRUCTION MODELS

LC focuses on eliminating non-value-adding activities to deliver value to the final customer. Its success hinges on the proper implementation of core practices and practices (Bajjou et al., 2019) . While many studies have sought to identify primary LC practices, researchers propose varying sets influenced by their backgrounds and conceptualization methods. This diversity highlights the challenge of establishing consistent LC practices as the concept evolves. To address this, an extensive literature review was conducted to identify validated LC practices that enhance construction project performance. Conceptual, empirical, and qualitative studies from 2000 to 2024 were analyzed to extract the most effective and commonly used practices. However, differing academic perspectives prevent consensus on classifying these practices.

As shown in Table 1, this study critically evaluates eight Lean Construction Models (LCMs) developed in countries with mature LC expertise, including the USA (Salem et al., 2006), the UK (Nesensohn et al., 2016), Germany and Brazil (Hofacker et al., 2008), Morocco (Bajjou et al., 2019; Bajjou & Chafi, 2023), and Malaysia (Jeni et al., 2013). The goal is to develop a comprehensive LC model by analyzing existing frameworks and addressing their limitations. For instance, the Lean Construction Framework (LCF) omits waste elimination and continuous improvement (Johansen & Walter, 2007), while the Lean Construction Maturity Model (LCMM) neglects supply chain management (Nesensohn et al., 2016). Other models exclude critical practices such as planning, customer involvement, and people engagement. Notably, none of the existing models validate their results in the context of megaprojects or within the Chinese construction industry using reliable techniques. This gap underscores the significance of the current study, which aims to enrich LC knowledge by providing a statistically validated framework for implementation, particularly tailored to megaprojects.

Table 1: Existing Lean Construction Models

	Bajjou and Chafi (2023)	**Bajjou et al.**(2019)	**Nesensohn et al.**(2016)	**Jeni et al.**(2013)	**Hofacker et al.**(2008)	**Johansen and Walter** (2007)	**Salem et al.**(2006)	**Diekmann et al.**(2003)
Customer Focus	☑	☑	☑	☑	☑	☑		☑
Waste Elimination	☑	☑	☑	☑	☑		☑	☑
People Involvement	☑	☑	☑			☑	☑	☑
Continuous Improvement	☑	☑	☑	☑	☑	☑	☑	
Supply Chain Management	☑	☑		☑	☑	☑		
Standardization		☑	☑	☑	☑			☑
Process Transparency	☑	☑	☑	☑	☑	☑	☑	☑
Planning and Scheduling	☑	☑	☑	☑	☑	☑	☑	
Quality Practices		☑	☑	☑	☑			

LEAN CONSTRUCTION PRACTICES

Integrated Project Delivery Systems (IPD) and Last Planner System (LPS): In IPD, risks are shared equitably among all parties. This fosters collective problem-solving and reduces adversarial relationships. IPD emphasizes the importance of early engagement and collaboration among all stakeholders, which is crucial in megaprojects where complexity and scale can lead to significant coordination challenges (Evans et al., 2023). LPS, on the other hand, focuses on the planning and scheduling of work at the execution level, ensuring that tasks are planned and executed efficiently, thereby reducing waste and improving productivity. LPS significantly elevated the organizational behaviour of the mega-project to a higher level of excellence. The commitment-driven nature of LPS proved to be invaluable, as it clearly delineated responsibilities for each team member, fostering accountability, ownership, and a sense of pride when targets were successfully met. A critical aspect of LPS is the validation of committed dates, which is essential to prevent the setting of unrealistic deadlines or under-commitment, ensuring that project timelines are both achievable and reliable (Ballard & Tommelein, 2016).

Value Stream Mapping (VSM) and Building Information Modelling (BIM): VSM is a lean tool that helps identify and eliminate waste in the value stream, thereby improving the flow of value to the customer. In construction megaprojects, VSM can be particularly effective in identifying bottlenecks and inefficiencies in the design and construction processes. BIM, as a digital representation of the physical and functional characteristics of a facility, provides a shared knowledge resource for information about a facility, forming a reliable basis for decisions during its lifecycle. The integration of BIM with lean practices in megaprojects lead to significant improvements in design coordination, construction sequencing, and overall project performance (Koskela et al., 2023; Meshref & Ibrahim, 2024).

Target Value Design (TVD) and Just in Time (JIT): TVD is a lean design approach that focuses on delivering projects within a defined cost target while maintaining quality and functionality. It encourages designers to think about cost and value early in the design process, which is particularly important in megaprojects where cost overruns are a common issue (Berawi et al., 2014). JIT is a production strategy that aims to minimize inventory and reduce waste by producing only what is needed, when it is needed. In construction, JIT can be applied to material and resource management, ensuring that materials and equipment are delivered to the site only when required, thereby reducing storage costs and improving efficiency.

METHODOLOGY

As illustrated in the **Figure 1**, the methodology for investigating Lean Construction Practices (LCPs) for adopting lean practices in construction megaprojects is systematically organized into distinct yet interrelated stages. It begins with a literature review to collect and synthesize existing knowledge about LC practices, laying the groundwork for the study. This is followed by data collection through interviews, where insights and opinions from industry professionals are gathered, enabling the initial categorization of practices with expert input. To ensure the quality and clarity of the research instrument, a pilot study is conducted, refining the questions to ensure logical structure, clarity, and appropriate timing. Once refined, the main survey is deployed to collect comprehensive data on the significance of lean adoption practices in construction megaprojects. The collected data is subjected to rigorous analyses, starting with reliability testing using Cronbach's Alpha (α) to ensure internal consistency and reliability of the survey instrument. Subsequently, the Fuzzy Relative Importance Index (FRII) is employed to rank and prioritize LC practices based on their relative importance as perceived by the participants. Finally, identifying the most critical practices for successful lean adoption in construction megaprojects is essential for organizations aiming to apply lean practices effectively.

LITERATURE REVIEW

Scopus, Web of Science (WOS), and Google Scholar are foundational databases widely used in construction management research. Among these, Scopus is particularly notable for its comprehensive repository, advanced citation tracking, and superior recall efficiency, especially in the social sciences. To explore LC research, a targeted search was conducted using Scopus's advanced document search functionality. Specific keywords and search strings were applied within the 'article title/abstract/keywords' fields, including "lean construction," "lean implementation factors," "lean activities," "lean practices," "lean tools," "lean techniques," and "megaprojects." Inclusion and exclusion criteria were rigorously applied to ensure relevance, as recommended by Ibrahim et al. (2024).

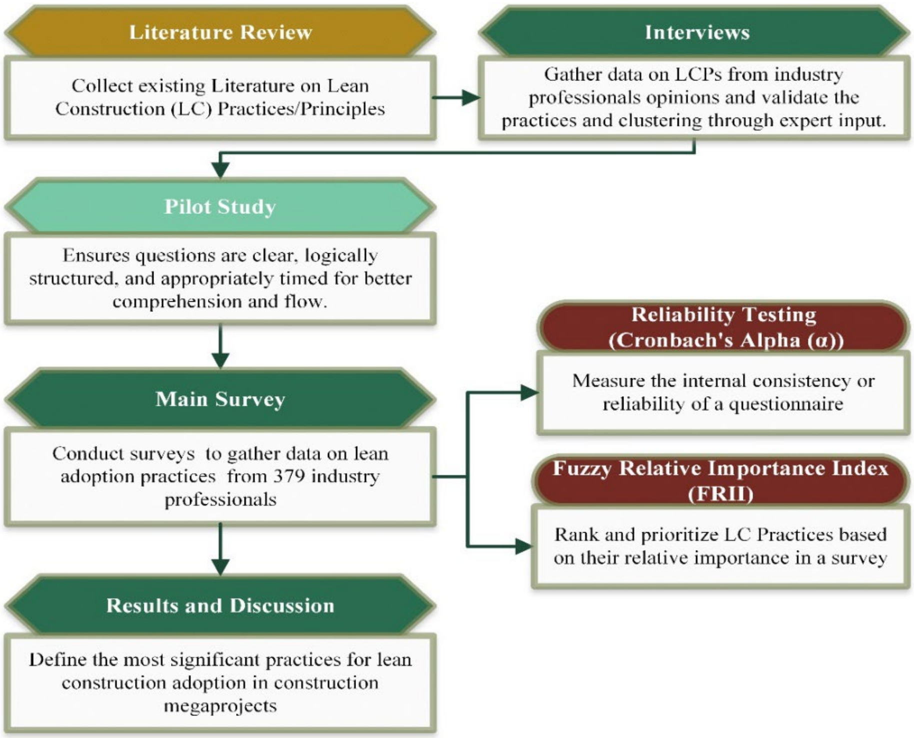


Figure 1: Research Methodology

Peer-reviewed journal articles and review papers published from 2000 onwards, in English, and with accessible full texts were prioritized, while non-relevant or outdated studies were excluded. To enrich the review further, the snowballing technique was employed, examining references and citations of selected articles to identify additional influential studies that may have been missed in the initial search (Ibrahim, Zayed, et al., 2024). After meticulous screening and refinement, 82 highly relevant papers were included in the final analysis.

SEMI-STRUCTURED INTERVIEWS

A thorough understanding of these practices is essential to enhance the efficiency and success of the construction industry. To gain deeper insights, semi-structured interviews were conducted with ten experts in construction megaprojects in China. These interviews were designed to explore the practices outlined above and examine their potential impact on LC implementation. The participants' industry experience ranged from 11 to over 25 years, with most holding advanced degrees (master's or Ph.D.). As a result, the list of practices has been updated, and modified some variables. The categorization of these practices, initially based on previous studies as mentioned in Table 1, was refined through interviews, resulting in the organization of the practices into six distinct groups as shown in Table 2.

Based on expert feedback, several adjustments were made Customer Focus and Waste Elimination were merged into "Customer Focus & Waste Elimination" to align their interconnected objectives, while People Involvement and Continuous Improvement were combined into "People Involvement & Continuous Improvement" to reflect their synergistic relationship. The principle of "Material Flow and Pull" remained unchanged due to its clarity and relevance, whereas Standardization and Process Transparency were merged to emphasize their complementary roles in project execution. Similarly, "Planning and Scheduling" was validated without modifications, and Quality Practices was rephrased as "Safety and Quality Assurance Practices" to better capture its scope. These refinements, informed by expert input, ensure the LC practices are both practical and well-suited to the complexities of megaprojects.

Table 2: LCPs to adopt lean construction in Construction Megaprojects (Babalola et al., 2019; Bajjou et al., 2019; Bajjou & Chafi, 2023)

LC Constructs	LC Practices/Tools
Customer Focus and Waste Elimination (CWE)	Optimize Value/Value Identification (CWE 1)
	Waste reduction strategy (reduce cycle time) (CWE 2)
	Customer Involvement (CWE 3)
	Target Value Design (TVD) (CWE 4)
	Value Stream Mapping (VSM) (CWE 5)
	Flexible Resources (CWE 6)
	Design workshops/big room workshop (CWE 7)
People Involvement and Continuous Improvement (PCI)	Gemba walks (PCI 1)
	Kaizen (PCI 2)
	Teamwork (PCI 3)
	Huddle Meeting (PCI 4)
	First run studies (PDCA) (PCI 5)
	Training/ Skills development (PCI 6)
	Metrics (productivity, quality, safety, environment) (PCI 7)
	A3 Report (PCI 8)
Flow and Pull Systems (FPS)	Pull Scheduling/planning (FPS1)
	Kanban system (FPS2)
	Just in Time (JIT) (FPS3)
	Integrated project delivery systems (IPD) (FPS4)
Standardization and Process Transparency (SPT)	Visual Management (VM) (SPT 1)
	Workplace Organization (5S) (SPT 2)
	Takt Time (SPT 3)
	Defined work process (SPT 4)
	Concurrent Engineering (SPT 5)
	Building Information Modelling (BIM) (SPT 6)
Planning and Scheduling (PAS)	Last Planner System (LPS) (PAS 1)
	PPC Charts (PAS 2)
	Collaborative Planning (PAS 3)
	Hoshin Management (PAS 4)
Safety and Quality Assurance practices (SQA)	Fail safe for quality (SQA1)
	Response to defect/Root cause analysis (five why, Ishikawa) (SQA2)
	Plan Conditions and Work Environment in the Construction Industry (PCMAT) (SQA3)
	Health/Safety Improvement (SQA4)
	Error Proofing (poke-yoke) (SQA5)
	Total Quality Management (TQM) (SQA6)

PILOT STUDY

To achieve the research objectives and validate the proposed model, a questionnaire survey was conducted in Hong Kong and Mainland China. These regions were chosen for their high concentration of megaprojects and shared regulatory and institutional frameworks.

Following the criteria suggested by Wang et al. (2021), the research focused on large-scale, complex projects with a total investment exceeding 0.5 billion CNY, identifying them as candidate megaprojects. The unit of analysis for this study is the megaproject itself. To ensure data accuracy and minimize hindsight bias, respondents were instructed to focus specifically on their most recently completed megaproject rather than their parent organizations. The targeted respondents included senior and middle managers who held key roles in project management and control during megaproject execution. Their insights were critical for understanding the complexities of megaproject delivery and aligning the data with the research objectives. Data collection occurred from March to September 2024 using stratified random sampling to ensure representation across various types of construction firms experienced in megaproject delivery. Out of 471 questionnaires received, 379 were deemed valid, achieving an effective response rate of 80.46%. A pilot study was conducted prior to the main data collection to assess the questionnaire's clarity, coherence, and completeness. Pilot studies are essential for ensuring that research methodologies align effectively with study objectives. The pilot questionnaire was reviewed by 10 specialists from diverse sectors, who provided feedback on question phrasing, validated survey practices, and identified areas for improvement. Based on their input, adjustments were made to enhance clarity and structure, ensuring the questionnaire was well-suited for the study. The questionnaire survey was selected as the primary data collection method due to its ability to generate quantitative data suitable for comprehensive statistical analysis.

FUZZY RELATIVE IMPORTANT INDEX (RII)

Relative Important Index (RII) was utilized in several studies in assigning relative importance index to various factors and consequently prioritizing these factors. Integrating fuzzy into RII mainly aims to account for uncertainty in the participants feedback due to subjective judgment. The general formula to compute RII is mentioned in Equation (1):

$$\text{Relative Important Index (RII)} = \frac{\sum \mathrm{W_i}}{A * N} \quad for\ i = 1\ to\ N \tag{1}$$

where "W" denotes the importance score assigned by respondents for each factor, "A" is the maximum possible score, and "N" is the total number of respondents in this study.

As each point on the Likert scale was presented by a triangle fuzzy number (TFN) as shown in Figure 2. Fuzzy arithmetic operations were adopted to apply Equation (3). The calculation of the RII followed four main steps, which are outlined in Figure 3 using a pseudocode format.

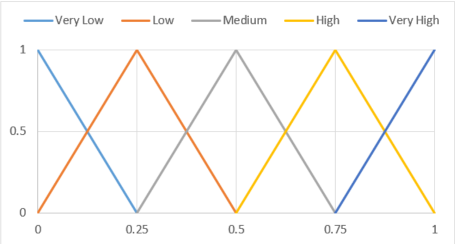
1. Calculate the numerator in Equation (1) (lines 1 to 5 in the pseudocode): The feedback from all participants was aggregated according to Equation (2). Equation (2) aggregates the feedback from any two participants, i.e., TFN1 = (a1, b1, c1) and TFN2 = (a2, b2, c2) as follows:
$$\mathrm{TFN_1(+)TFN_2} = (\mathrm{a_1 + a_2\,, b_1 + b_2\,, c_1 + c_2}) \tag{2}$$
2. Applying α-cut (lines 6 to 8): Since the application of the fuzzy division operator generates a polynomial membership function (i.e., not a triangular), the α-cut approach was applied to the triangular fuzzy numbers of the numerator (the aggregated value from step 1) and the highest score. The α-cut of a fuzzy set A comprises the elements of A that have the same membership value. α-cut values should be limited to the interval [0, 1].
3. Calculate the fuzzy-RII (line 9): The values generated from the α-cut in the previous step, combined with the division operator, were used to construct the membership function of the fuzzy-RII. For two intervals of α-cut, i.e., Aα = [AαL, AαU] and BL, [BαL, BαU], the division operator can be applied as follows using Equation (3):
$$A\alpha(/)B\alpha = \left[\frac{\mathrm{A\alpha_L}}{\mathrm{B\alpha_U}}, \frac{\mathrm{A\alpha_U}}{\mathrm{B\alpha_L}}\right] \tag{3}$$

By considering the formula in Equation (1), the values of the fuzzy-RII at specific α-cut can be determined using the following Equation (4):

$$RII\alpha = \left[\frac{W\alpha_L}{N * A\alpha_U}, \frac{W\alpha_U}{N * A\alpha_L}\right] \tag{4}$$

4. Defuzzify the RII (lines 11 to 13): The fuzzy RII obtained from Equation (4) was defuzzified using the geometric centroid approach (Equation (5)) to convert the fuzzy-RII into a crisp-RII. Defuzzification is the process to transforming a fuzzy number Fi to a crisp value.

$$GC(Fi) = \frac{\int x\mu_A(x)\,dx}{\int \mu_A(x)dx} \tag{5}$$



Linguistic Term	Triangular Fuzzy Numbers
Very low	[0.0 0.0 0.25]
Low	[0.0 0.25 0.5]
Medium	[0.25 0.5 0.75]
High	[0.5 0.75 1.0]
Very high	[0.75 1.0 1.0]

Figure 2: Equivalent TFN for Likert scale

Algorithm: Calculate RII

```
1   for X (factor) = 1 to m:
2       Initialize summation = (0,0,0) = W
3       for P(participant) =1 to N:
4           Add participant's feedback (TFN score) to summation
5       end for
6       for α-cut = 0 to 1:
7           Aα (highest score) = [ Aα_L , Aα_U]
8           Wα (summation) = [ Wα_L , Wα_U]
9           RIIα = [ Wα_L / (N* Aα_U) , Wα_U/ (N* Aα_L)]
10      end for
11      Calculate Defuzzified-RII
12  end for
13  Rank various factors based of the Defuzzified-RII
```

Figure 3: Pseudocode to calculate RII

RESULTS AND DISCUSSION

Evaluation of Reliability

Before proceeding with the main analysis, the internal consistency of the scale used to rate challenges and strategies was evaluated using Cronbach's Alpha, a Cronbach's Alpha score of 0.70 or higher signifies satisfactory internal consistency. In this study, the test produced a score exceeding .971 for all practices, demonstrating exceptional reliability of the Likert scale employed.

Demographic Profiles

The demographic profile of construction industry respondents reveals key insights into their professional backgrounds. The majority (63.85%) were from Mainland China, with 36.15% from Hong Kong, reflecting a focus on two major construction markets. Residential projects were the most common (43.54%), followed by infrastructure/transportation (29.02%) and commercial projects (16.89%). Respondents were highly experienced, with 55.15% having 11-15 years of experience and 26.39% having 6-10 years. Many had participated in megaprojects (28.76% in over three, 29.29% in three). Contractors formed the largest group (50.13%), followed by consultants (28.23%) and owner/client representatives (21.64%). Most respondents were familiar with Lean practices (40.37% somewhat, 30.08% moderately, 26.39% very familiar), indicating growing Lean adoption.

Significant LCPs for Lean Adoption in Construction Megaprojects

Table 3 presents a comprehensive assessment of LCPs for megaprojects, showcasing highly reliable survey data with Cronbach's Alpha of .971. The statistical analysis reveals significant variations in the implementation and effectiveness of different LC practices, with all assessed practices assessing statistical significance ($p < .05$).

Table 3: Assessment of LC Practices for Megaprojects (Survey and Statistical Analysis)

Activity Code	Percentage of Respondents Scoring					Mean	FRII	Rank by category	Level of Imp
	VL	L	M	H	VH				
Customer Focus and Waste Elimination (CWE)									
CWE 1	3.43	10.03	27.97	37.47	21.11	3.628	0.737	5	M-H
CWE 2	2.90	9.76	33.25	31.40	22.69	3.612	0.731	6	M-H
CWE 3	2.90	7.92	27.70	40.37	21.11	3.689	0.754	4	M-H
CWE 4	2.64	5.80	20.32	34.04	37.20	3.974	0.815	1	H
CWE 5	2.90	6.86	22.16	24.27	43.80	3.992	0.813	2	H
CWE 6	2.90	8.44	31.93	37.20	19.53	3.620	0.736	7	M-H
CWE 7	2.11	6.86	21.90	35.62	33.51	3.916	0.802	3	M-H
People Involvement and Continuous Improvement (PCI)									
PCI 1	2.4	10.8	29.0	34.3	23.5	3.691	0.742	8	M-H
PCI 2	2.1	6.6	29.8	37.7	23.7	3.760	0.765	2	M-H
PCI 3	3.2	7.9	26.1	40.9	21.9	3.620	0.757	5	M-H
PCI 4	2.1	6.9	27.7	39.1	24.3	3.826	0.771	1	M-H
PCI 5	3.2	7.7	30.6	37.7	20.8	3.913	0.745	7	M-H
PCI 6	2.9	7.7	28.5	35.1	25.9	3.752	0.761	4	M-H
PCI 7	2.6	7.1	28.0	38.5	23.7	3.958	0.764	3	M-H
PCI 8	2.4	6.6	31.9	38.5	20.6	3.681	0.752	6	M-H
Flow and Pull Systems (FPS)									
FPS1	2.11	7.65	29.02	40.11	21.11	3.704	0.757	3	M-H
FPS2	1.85	8.71	32.98	34.83	21.64	3.657	0.743	4	M-H
FPS3	2.37	8.18	24.27	33.51	31.66	3.839	0.783	2	M-H
FPS4	0.53	3.17	16.89	36.68	42.74	4.179	0.864	1	H
Standardization and Process Transparency (SPT)									
SPT1	2.64	7.65	30.61	35.88	23.22	3.694	0.752	4	M-H
SPT2	3.17	7.65	30.61	37.73	20.84	3.654	0.745	6	M-H
SPT3	2.11	8.18	30.34	31.40	27.97	3.749	0.762	2	M-H
SPT4	2.64	10.29	26.65	37.20	23.22	3.681	0.749	5	M-H
SPT5	2.64	10.29	25.86	35.36	25.86	3.715	0.755	3	M-H
SPT6	2.11	6.33	18.47	35.88	37.20	3.997	0.821	1	H
Planning and Scheduling (PAS)									
PAS1	2.11	5.01	17.41	34.04	41.42	4.077	0.838	1	H
PAS2	1.58	6.33	24.27	39.58	28.23	3.865	0.794	3	M-H
PAS3	1.85	7.12	23.22	34.04	33.77	3.908	0.799	2	M-H
PAS4	2.90	9.50	24.01	40.90	22.69	3.710	0.758	4	M-H

Safety and Quality Assurance practices (SQA)									
SQA1	2.37	8.97	25.59	33.25	29.82	3.792	0.772	2	M-H
SQA2	3.17	7.92	26.12	40.90	21.90	3.704	0.757	6	M-H
SQA3	2.90	7.39	25.86	34.83	29.02	3.797	0.775	1	M-H
SQA4	2.37	7.92	28.23	33.25	28.23	3.770	0.768	3	M-H
SQA5	3.43	7.92	27.44	34.56	26.65	3.731	0.760	5	M-H
SQA6	1.58	8.71	27.70	35.88	26.12	3.763	0.767	4	M-H

Note: The Shapiro-Wilk test results at the significance level of 0.05 (p-value < .05).

According to the FRII values, the practices can be categorized into two main groups: those with high importance (FRII > 0.8) and those with medium to high importance (FRII between 0.6 and 0.8). This distinction highlights the varying levels of criticality among the Lean Construction practices, with the high-importance factors being particularly essential for driving efficiency and success in megaprojects. Notably, practices such as IPD (FPS4), LPS (PAS 1), VSM (CWE 5), BIM (SPT 6), TVD (CWE4), Metrics (productivity, quality, safety, environment) (PCI 7), Collaborative Planning (PAS 3), Design workshops/big room workshop (CWE 7), PDCA (PCI 5), and JIT (FPS3) exhibit the highest FRII scores and rankings, indicating their strong implementation across megaprojects.

CONCLUSIONS

This study bridges the gap between theory and practice in LC for megaprojects by identifying, validating, and prioritizing 35 key LC practices. Using a mixed-methods approach, including a systematic literature review, expert interviews, and a survey of 379 construction professionals, the study highlights five critical practices: Integrated Project Delivery (IPD), Last Planner System (LPS), Value Stream Mapping (VSM), Building Information Modelling (BIM), and Target Value Design (TVD). These practices enhance efficiency, collaboration, and sustainability while addressing challenges like complexity, scale, and coordination in megaprojects. Adopting these practices can improve productivity, reduce waste, enhance quality, and ensure safer, more sustainable construction. Theoretically, the study advances the understanding of LC in complex projects, while practically, it provides actionable insights for industry leaders and policymakers to prioritize impactful strategies. The findings suggest that implementing these practices can lead to improved efficiency, reduced costs, better project outcomes, and minimized environmental impact, emphasizing the importance of collaboration and innovation in transforming the construction industry. Therefore, the findings may offer valuable insights into other regions, albeit with adaptations to local contexts. For example, practices like Integrated Project Delivery (IPD) and the Last Planner System (LPS) have been successfully applied in various international contexts, suggesting their broad relevance. However, it is important to acknowledge that the conclusions are based on the experiences and perspectives of Chinese megaproject managers, who can only report on the LC practices they have used. While these insights are valuable, they may not fully capture the diversity of practices and contexts in other regions. Therefore, the findings should be interpreted with caution, and further research is needed to validate and expand these results in diverse geographical and cultural contexts. In terms of future research, this study highlights the need to explore not only what LC practices to implement but also how to implement them effectively. Future studies could investigate the sequence and interdependency of practices, as well as the development of frameworks for integrating LC practices into megaproject delivery. Additionally, expanding the sample size and geographical scope of the study would increase the generalizability of the findings and provide deeper insights into the long-term impacts.

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